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A Multi-dimensional Assessment of Ecologically Sensitive Areas: A Case Study of Ziqing in Nanjing

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Abstract

With the acceleration of urbanization in China, many cities are subjected to negative impacts. This project focuses on protecting the ecological environment of Ziqing in Nanjing by applying Geographic Information System (GIS) to enhance ecological protection and address environmental issues. GIS can aggregate, analyze, and visualize spatial data, serving as one of the tools available during the selection process for Ecologically Sensitive Areas (ESAs). Ecological sensitivity refers to the extent to which ecosystems respond to human activities and changes in the natural environment, reflecting the likelihood of ecological problems arising at a regional scale. In this study, the ecological sensitivity of Ziqing is evaluated through model construction and factor selection. This research explores the current applications of classification and data processing in GIS, as well as the potential of spatial analysis in site selection and microclimate improvement. The project applies both ecological and infrastructural indicators in the evaluation of ecological sensitivity, from factor selection to the assessment of ecological sensitivity zoning. It combines various methods such as the Delphi Method, Analytic Hierarchy Process, and Overlaying Analysis to provide a multi-dimensional evaluation of the landscape environment in Ziqing, offering a basis for future protection and development efforts.

Keywords

Urbanization, Ecologically Sensitive Areas (ESAs), Multi-dimensional Methods, Geographic Information System (GIS)

1. Introduction

In recent decades, the direct transformation of landscape patterns has been a consequence of rapid human activities, which have also impacted ecosystem structure and function, and significantly undermined ecosystem health [1]. As epicenters of industrial growth and socio-economic activity, urban areas are subject to some of the most pronounced alterations in landscape patterns [2]. Land urbanization in China, particularly in terms of land expansion, has progressed much faster than demographic urbanization over the past two decades. The factors contributing to this situation include the loss of arable land, diminished biodiversity, and increased landscape fragmentation. Additionally, air pollution, deteriorating water quality, and water shortages, which affect two-thirds of Chinese cities, are also responsible for this phenomenon [3]. By 2030, it is estimated that 70% of China's population will be living in urban areas. In order to inform sustainable planning and design for citizens, it is necessary to pay attention to landscape patterns and ecological changes during urbanization [4]. Land urbanization raises significant concerns regarding Ecological Sensitivity (ES), primarily because it often leads to the fragmentation and degradation of natural habitats. As urban areas expand, natural landscapes are impacted due to the construction of infrastructure, disrupting the delicate balance of local ecosystems. The rapid expansion of urban land also encroaches on Ecologically Sensitive Areas (ESAs), posing a significant threat to the integrity of urban ecological systems. Urban ESAs refer to ecological elements or entities located within and around cities that hold ecological importance for the urban environment but have limited capacity for recovery if damaged by urbanization [5].

To safeguard urban areas and mitigate the negative impacts of urban development, studies have focused on the protection of ESAs. For assessments of ESAs in 2011, indicators including soil conditions, water quality, atmospheric conditions, and biodiversity were utilized to evaluate ES. A spatial distribution map of environmental sensitivity for urban planning and design was generated using Geographic Information System (GIS) techniques [6]. In 2015, evaluations of ESAs were conducted using a standard grading system, with importance levels or weights determined through the Analytic Hierarchy Process (AHP) [7]. In 2023, scholars established an ecological vulnerability evaluation system for ESAs' appraisements, selecting impact factors and processing relevant datasets [8]. However, existing researches on ESAs primarily focus on either grey infrastructure or ecological space respectively with the application of linear methodologies (Fig. 1). Applying multi-dimensional methodologies that combine construction and nature can lead to more sustainable urban developments. There should be approaches to integrating various disciplines and perspectives to address the complex interactions between built environments and natural ecosystems.

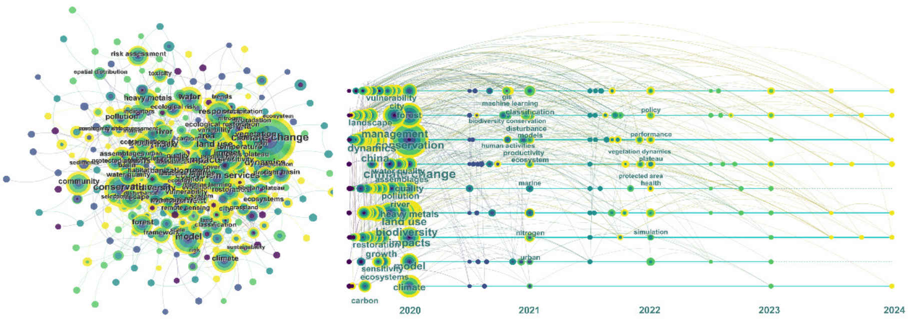

Figure 1. The Interconnected Fields in ESAs Researches from 2020 to 2024 (Source: the author).

2. Methodology

2.1 Study Area

The site, Ziqing, is located in Nanjing, situated in the Yangtze River Delta, China. Nanjing is one of the most dynamic and innovative cities in China, attracting a large influx of population. At the same time, Nanjing has a superior level of urbanization, while requiring ecological restoration. According to the blue-green system analysis of Nanjing, there lies severe fragmentation in Nanjing's natural spaces, necessitating the revitalization of ESAs. Multitudes of sampling blue-green spaces are small-scale (Fig. 2). Ziqing, as a site with natural blue-green space, has affluent natural resources while rapid urbanization brings dangers to habitat loss and biodiversity decline. Ziqing is located near the entrance of the Tangshan Scenic Area on the north side of the Huning Expressway. There is a natural lake, Ziqing Lake, which is home to the nationally protected species, the Yangtze alligator. The lakeshore and highlands are densely populated with vegetation. However, some existing buildings and facilities have caused damage to the ecological environment of Ziqing Lake.

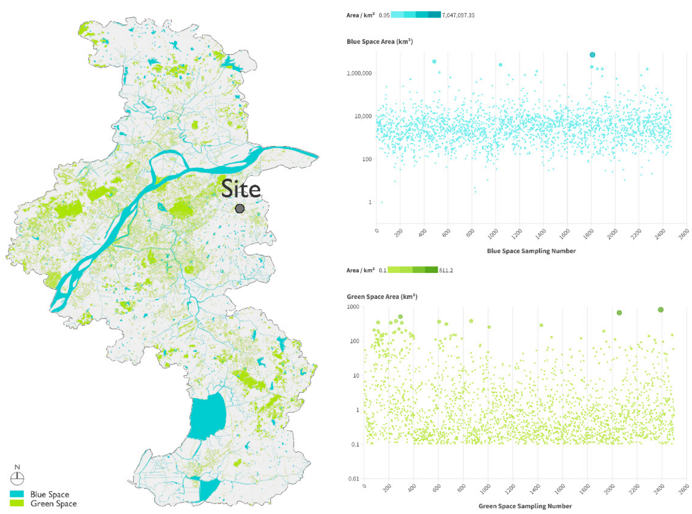

Figure 2. The Site Location and Sampling Blue-green Space Areas (Source: the author).

2.2 Evaluation Framework

The evaluation framework includes multi-dimensional principles of assessment, including man-made construction and natural environment. This study conducts a final evaluation of ES through four steps: constructing a hierarchical model, selecting evaluation factors, determining factor weights, and delineating ESAs (Fig. 3). The main methods for evaluating ES in Ziqing include the Delphi Method (DM), Analytic Hierarchy Process (AHP), and Overlaying Analysis (OA).

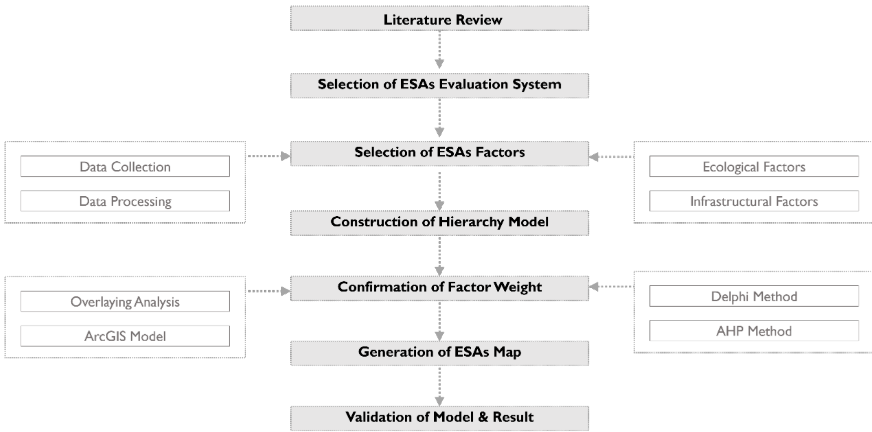

Figure 3. The ESAs Evaluation Framework (Source: the author).

The DM is a systemic communication technique initially developed as a structured, interactive forecasting method relying on expert groups [9]. In this study, DM involves surveying a panel of landscape experts to reach a consensus. Experts respond to several rounds of questionnaires, and after each round, the evaluation factors' scores are summarized and shared with the group. The AHP, a structured method based on mathematical and psychological comprehension, organizes and analyzes complex decisions [10]. The AHP helps decision-makers identify the best-assessing methods aligned with the ultimate goals and understanding of the ESAs' problems. It provides a comprehensive and rational framework for structuring ESAs' issues, representing and quantifying the ecological and infrastructural elements, and linking these elements to overall objectives for ESAs' evaluation. OA is one of the most commonly used methods in the Geographic Information System (GIS) for extracting spatial information. This method originates from the traditional stacking of transparent layer materials. In GIS, the objective of OA is to create new data layers by stacking existing data layers composed of thematic layers. The resulting overlay integrates the attributes of the original layers. The objective of OA is not only to compare spatial relationships but also to compare attribute relationships. In GIS, OA is mainly divided into two categories: vector overlaying and raster overlaying.

2.3 Evaluation Method

The ES assessment is conducted using the ArcGIS platform. First, spatial data is collected and arranged according to its relevance to this study. At a fundamental level, qualitative data can be directly input into the GIS. Various visualization techniques can incorporate non-numeric data forms into map layers. These visualizations can represent multiple environmental implications from ecological and infrastructural aspects. The reclassification workflow begins with symbolizing raster layers for display, using different classification algorithms. The visualization layers are created by the classification settings, and the classification intervals are acquired from the experts (Fig. 4).

Factor Typology	Primary Factor	Weight	Secondary Factor	Weight	Grading Standard		
					High Sensitivity	Moderate Sensitivity	Low Sensitivity
Ecological	Topography	0.2667	DEM	0.0874	>100m	30-100m	<100m
			Slope	0.1101	>30°	15°-30°	<15°
			Aspect	0.00693	North	Northwest, Northeast	South, Southwest, Southeast
	Soil	0.16	Agrotype	0.12	Clay Soil	Loam Soil	Sandy Soil
			Organic Soil	0.04	>20%	10%-20%	<10%
	Hydrology	0.16	Runoff Buffer	0.0533	<50m	50-100m	>100m
			Water Buffer	0.1067	<20m	20-50m	>50m
	Vegetation	0.2847	Vegetation Coverage	0.1437	Dense	Sparse	Bare
			Floristics	0.0719	Coniferous Forest	Broadleaf Forest	Grassland
			Vegetation Growth	0.0719	Good	Average	Bad
	Animal	0.0732	Alligator Habitat	0.0732	50m	50-100m	>100m
Infrastructural	Construction	0.0526	Land Use	0.0526	Unbuilt Area	Vacant Area	Built-up Area

Figure 4. The Factor Weight Chart of ESAs (Source: the author).

Ultimately, reclassified maps of topography, hydrology, vegetation, soil, and construction status are produced (Fig. 5). Spatial overlay analysis is then implemented, based on a multi-factor evaluation model. The raster overlaying calculations are performed using the weights of ESAs' factors to obtain a composite sensitivity value.

In this project, the exploratory analytical capabilities of GIS assist in identifying spatial features within both qualitative and quantitative data. While studying the ecological sensitivity of a region, the environmental status and ecosystem service are also examined and overlaid to derive ecologically functional zoning, which can effectively guide the protection and development of Ziqing. Regional ecosystems are complex entities influenced by multiple factors rather than a single determinant. The ESAs are affected by various elements, including topography, hydrology, vegetation, soil, and construction. This study analyzes the differentiation patterns of ecological sensitivity regions based on the mechanisms of major environmental factors, clarifying the possible spatial protection in Ziqing, maintaining regional biodiversity security, and supporting sustainable economic development.

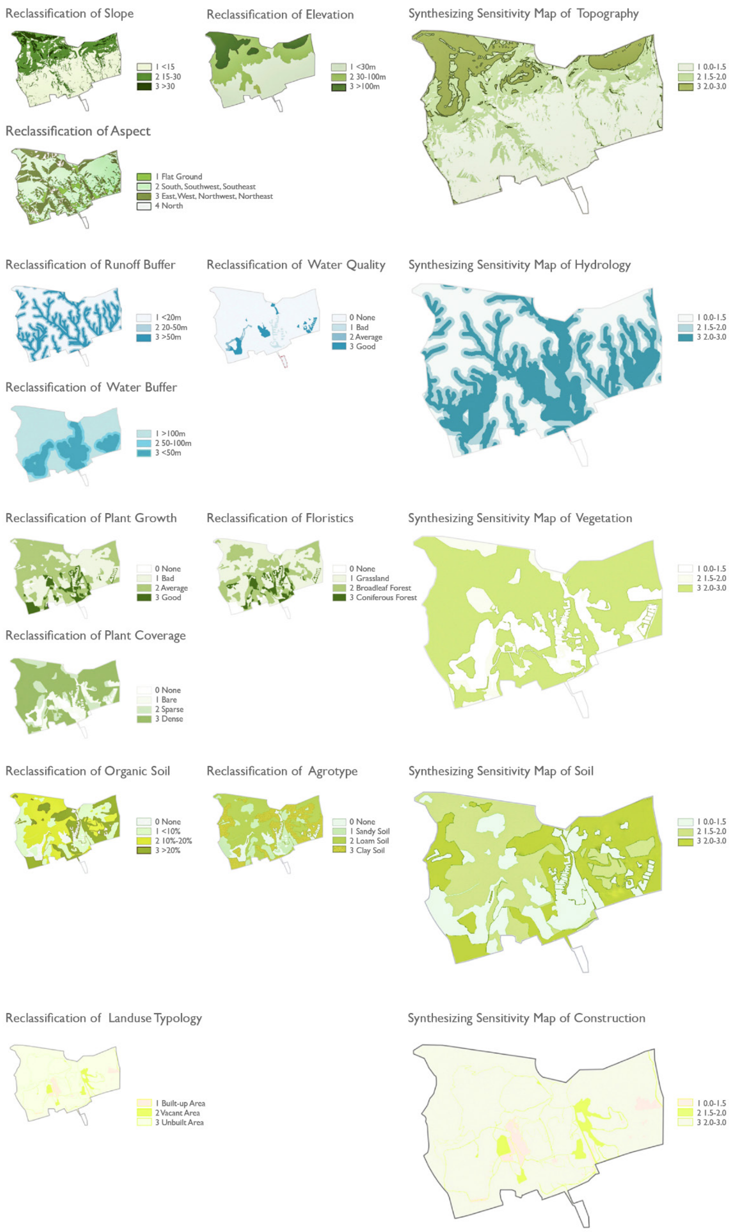

Figure 5. The Reclassification Maps (Source: the author).

3. Result

Based on the analyzed weights, a comprehensive ES index is derived. The sensitivity index calculated is classified using GIS software, and the ESA map is created. A weighted overlay of the factor evaluation results is performed, with the overlay rule being:

$$S = \sum_{i=1}^{n} W_i P_i$$

S: Sensitivity Level, W_i: Factor Weight, P_i: Score of Factor.

The topography factor and vegetation factor account for 55.14% of the total weight, which indicates that the flora and terrain play significant roles in ESAs' protection. Based on the natural break method, the calculated sensitivity values are reclassified into three categories corresponding to three levels of environmental sensitivity. The ESAs' evaluations are ultimately obtained through the weight calculation in GIS (Fig. 6).

Figure 6. The ESA Map (Source: the author).

Natural geographical conditions, climatic factors, and human activities determine the impact of environmental changes in Ziqing. Regions with high ecological sensitivity are primarily concentrated in the northern mountainous areas, where the vegetation is predominantly forested, elevations are higher, and slopes are steeper. The central and southern areas are flatter, mainly consisting of grasslands, with a denser population that has a stronger adaptability to human activities, resulting in less impact from human activities and natural environmental changes. The probability of environmental degradation in the southern region is lower than in the northern region. However, ecological damage and pollution issues still exist in southern areas due to historical urban aggregation processes.

Ecosystems can be harmed and the functions of ecosystem services diminished due to inappropriate reclamation, deforestation, overgrazing, predatory fishing, and other unsustainable human activities [11]. Therefore, the regeneration of biodiversity should be a priority to ensure the protection and restoration of habitats for various plant and animal species, thereby maintaining the ecological balance in Ziqing. In highly sensitive areas, sustainable ecological forest resource management strategies must be implemented, ensuring the integrity and health of ecosystems while developing resources. To achieve this goal, large areas of land should be reallocated for afforestation, focusing on ecological restoration. This process includes controlling soil erosion, preventing land degradation, and achieving carbon sequestration through reforestation and the restoration of natural vegetation to mitigate climate change impacts. In moderately sensitive areas, protecting water sources from pollution is crucial. This involves not only direct protection of water bodies but also managing the surrounding environment to prevent negative impacts from industrial activities on water sources. The scale and scope of industrial development should be limited to ensure it does not threaten water resources. At the same time, sustainable agriculture and other low-impact economic activities should be encouraged to achieve reasonable resource utilization and ecological protection. In low-sensitive areas, moderate development is feasible. Development activities should consider environmental impacts and prioritize green and sustainable technologies to ensure a balance between economic development and ecological protection. The connotation of ecological protection is not merely an ecological classification in space, rather, it is a comprehensive consideration of the area's social-ecological system from a systematic perspective [12]. Through the implementation of effective planning and management strategies, it is possible to achieve a mutually beneficial outcome that encompasses economic and ecological advantages. This approach serves to establish a foundation for future sustainable development.

4. Conclusion

The multi-dimensional ESAs' assessment based on GIS technology provides guidance on how to effectively reduce the potential damage to the ecological environment caused by urban expansion. Sensitive areas do not imply that humans are prohibited from engaging in any activities; rather, they encourage greater attention to ecological protection and the implementation of appropriate measures in urban construction.

From the ESA map, it can be seen that areas of high ecological sensitivity are mainly distributed in the central and northern mountainous regions, where the central area has abundant water resources, the northern area has more forests, and the elevation is higher. Moderately sensitive areas are mainly found in the southern, eastern, and western regions. Low-sensitive areas are primarily concentrated in the southern plains and paddy fields, where the terrain is flat and sensitivity is below the average level.

The assessment indicators mainly include two aspects: ecological and infrastructural. Key indicators include topography, soil, hydrology, flora, fauna, and construction. Secondary indicators include relative elevation, slope, aspect, soil type, soil organic matter, water body buffer zones, watershed buffer zones, vegetation coverage, vegetation types, vegetation growth, endangered species habitats, and construction status. The grading standards include three levels: high sensitivity, moderate sensitivity, and low sensitivity, assigned scores of 3, 2, and 1, respectively.

As the intensity of urbanization disturbances increases, the effects of ecological and infrastructural factors in the evolution of ecosystem services vary from region to region [13]. The results of the multi-factor impact analysis indicate that anthropogenic activities, particularly urbanization and the development of advanced man-made structures, have a more pronounced impact on the ecosystem in Ziqing.

While this research in ecological sensitivity assessment involves a broad range of evaluation factors, it has limitations in considering spatiotemporal indices. The lack of attention to how environmental factors change over time and across different spatial scales may lead to an incomplete understanding of ecological dynamics. Moreover, this study primarily concentrates on natural and social factors, with economic factors excluded from the evaluation model.

The incorporation of spatiotemporal indices of natural, social, and economic values could serve to enhance the assessment by providing insights into the manner in which sensitivity varies with seasonal changes, land-use shifts, and climatic variations. Such an approach would facilitate the development of more effective planning and management strategies that account for both current conditions and future projections.

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